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Galaxy And Mass Assembly (GAMA): in search of Milky Way Magellanic Cloud analogues

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ABSTRACT

Analysing all Galaxy And Mass Assembly (GAMA) galaxies within a factor of 2 ($\pm$0.3 dex) of the stellar mass of the Milky Way (MW), there is a 11.9 per cent chance that one of these galaxies will have a close companion (within a projected separation of 70 kpc and radial separation of 400 km s^{-1}) that is at least as massive as the Large Magellanic Cloud (LMC). Two close companions at least as massive as the Small Magellanic Cloud (SMC) are rare at the 3.4 per cent level. Two full analogues to the MW–LMC–SMC system were found in GAMA (all galaxies late-type and star-forming), suggesting that such a combination of close together, late-type, star-forming galaxies is rare: only 0.4 per cent of MW mass galaxies (in the range where we could observe both the LMC and SMC) have such a system. In summary, the MW–LMC–SMC system is a 2.7σ event (when recast into Gaussian statistics).

Using cross-correlation comparisons we find that there is a preference for SMC–LMC binary pair analogues to be located within 2 Mpc of a range of different luminosity groups. There is a particular preference for such binaries to be located near Local Group luminosity systems. When these groups are subdivided into small magnitude gap and large magnitude gap subsets, the binaries prefer to be spatially associated with the small magnitude gap systems. These systems will be dynamically less evolved, but still offer the same amount of gravitational dark matter. This suggests that binaries such as the SMC–LMC might be transient systems, usually destroyed during vigorous merger events. Details of a particularly striking analogue to the MW–SMC–LMC and M31 complex are included.

Key words: galaxies: haloes – galaxies: kinematics and dynamics – Local Group – Magellanic Clouds – large-scale structure of Universe.

1 INTRODUCTION

The Local Group (LG), and more specifically the Milky Way (MW), is the most thoroughly explored dark matter complex in the Universe (e.g. Mateo 1998; van den Bergh 2000; Benson et al. 2002; Karachentsev et al. 2009; Font et al. 2011). However, question marks remain over how typical the MW halo is in the context of the Universe and how unusual its galaxy occupation statistics

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are (e.g. Boylan-Kolchin, Bullock & Kaplinghat 2011; Lovell et al. 2011; Tollerud et al. 2011; Weisz et al. 2011). It is important that we fully understand how representative the MW halo is since, by virtue of proximity, it will always be the environment that will contain the faintest known galaxies and the broadest range of galaxy masses. It will also be the halo from which we can derive the most information about its formation history. Knowing which satellites of the MW halo are typical within similar-mass similar-redshift haloes will either severely tighten or relax the predictive requirements of N-body semi-analytic galaxy formation codes. Currently it is acknowledged that simulations struggle to predict the full distribution of MW satellite galaxies; these problems are particularly manifest for the brightest satellites: Large Magellanic Cloud and Small Magellanic Cloud (LMC and SMC) (e.g. Benson et al. 2002; Koposov et al. 2009; Okamoto et al. 2010).

We are set to learn a vast amount about the MW halo in the coming decades. In the near future *Gaia* (Wilkinson et al. 2005) will measure space motions and properties for two billion stars in the LG which includes all known member galaxies. Amongst likely discoveries, we will learn about dynamical equilibrium or lack of it, for the first time. Building up to these hugely detailed surveys it is important that we discover where the MW halo fits into the bigger picture. Only then can we apply what we know about the MW to the Λ cold dark matter (ΛCDM) (or some variant) model of the Universe. Combining near-field cosmology (LG scale) and far-field cosmology (redshift surveys) is key to completing the full picture of galaxy formation (Freeman & Bland-Hawthorn 2002).

This work puts the investigation of the MW halo into an observational cosmological context by using data from the Galaxy And Mass Assembly (GAMA) project. GAMA is a multiwavelength photometric and spectroscopic survey, and was designed to answer questions about how matter has assembled on a huge variety of scales: filaments, clusters, groups and galaxies. The first phase of the redshift survey was conducted on the Anglo-Australian Telescope (AAT) (known as GAMA-I) and these data are used in this work (Driver et al. 2011). In this work we use GAMA redshifts to search for close companions to MW mass galaxies. These systems will be MW Magellanic Cloud analogues (MMAs from here). We use this sample to construct statistics on the rarity of SMC- and LMC-type (star-forming late-type galaxies) close companions around L^* late-type moderate star formation rate spiral galaxies like our own MW.

In Section 2 we discuss the data used in this work in detail. In Section 3 we present the statistics for finding MW–LMC and MW–LMC–SMC type systems, allowing us to quantify the apparent rarity of MW-like systems. In Section 4 we investigate the environment that SMC–LMC type binaries are most commonly located in, and relate this to some of the defining characteristics of the LG.

Data for the LG were calculated using distance indicators without any H_0 dependence. As such it is appropriate (and consistent with the main body of LG literature) to convert GAMA data into true distance. To make the appropriate conversions we take the latest 7-year *Wilkinson Microwave Anisotropy Probe* (*WMAP*7) cosmology: $\Omega_{\rm M} = 0.27$, $\Omega_\Lambda = 0.73$ and $H_0 = 70\,{\rm km\,s^{-1}}$ (Komatsu et al. 2011).

2 DATA

The GAMA project is a major new multiwavelength spectroscopic galaxy survey (Driver et al. 2011). The first three years of data obtained are referred to as GAMA-I, and are the data used for this work. The GAMA-I data used here contain ~86 K redshifts to $r = 19.4$ over ~144 deg^2, with a survey design aimed at providing an exceptionally uniform spatial completeness and high close pair completeness (Baldry et al. 2010; Robotham et al. 2010; Driver et al. 2011).

Table 1. Data used in this work. Data origin: van den Bergh (2000)[a], assumed M31 values for MW property[b], Flynn et al. (2006)[c], Nasa Extragalactic Database[d], James & Ivory (2011)[e] and Nichols et al. (2011)[f]. All magnitudes used are intrinsic, i.e. $H_0 = 70\,{\rm km\,s^{-1}}$. M_r is derived using M_V and the $B-V$ colour using the relevant Lupton SDSS photometric transform equation[1].

Name	M_V	$B-V$	M_r	$\mathcal{M}$ (M$_\odot$)	D (kpc)	V_R/V_T (km s^{-1})
MW	−20.90[a]	0.9[b]	−21.17	5×10^{10}[c]	0	0
LMC	−18.50[a]	0.5[d]	−18.60	2.3×10^{9}[e]	50[f]	89/367[f]
SMC	−17.10[a]	0.5[d]	−17.20	5.3×10^{8}[e]	60[f]	17/301[f]

Extensive details of the GAMA survey characteristics are given in Driver et al. (2011), with the survey input catalogue described in Baldry et al. (2010) and the spectroscopic tiling algorithm in Robotham et al. (2010). Additional data used for this work are stellar masses (Taylor et al. 2011) and GAMA Galaxy Group Catalogue (G^{3}Cv1) groups (Robotham et al. 2011).

Table 1 shows the important MW, LMC and SMC values used for this work including distance and radial/tangential velocity separations to the MW. Conversions to the native GAMA r band are made using the Lupton transforms.[1]

3 FINDING MW MAGELLANIC CLOUD ANALOGUES

There are a number of questions that could be stated with respect to investigating MMAs. For clarity this section answers the following: 'how common is it to observe one or two relatively large (stellar mass $>1 \times 10^8\,{\rm M_\odot}$), star-forming satellites close to galaxies with stellar masses within 0.3 dex of the MW?' While this question lacks simplicity, it is at least possible to answer it in a meaningful, and reproducible, manner. This is a pertinent question to ask, since galaxy formation models have trouble replicating the presence of very bright satellites in close proximity to simulated galaxies like the MW (e.g. Benson et al. 2002).

First we define 'similar' stellar mass to mean within 0.3 dex of the MW mass ($\mathcal{M}_{\rm s-MW} = 5 \times 10^{10}\,{\rm M_\odot}$; Flynn et al. 2006). Similarly we have to quantify 'close'. A number of studies have been contacted that allow us to estimate the SMC/LMC distance and radial/tangential velocity components. Much endeavour has been invested in proper motion measurements by multiple teams (e.g. Kallivayalil et al. 2006a; Kallivayalil, van der Marel & Alcock 2006b; Costa et al. 2009; Vieira et al. 2010; Costa et al. 2011) which has allowed the more difficult to observe tangential velocity components to be estimated. These numbers have been further refined by detailed simulations (e.g. Bekki 2008; Nichols et al. 2011). The SMC is ~60 kpc from the MW and travelling radially away at ~17 km s^{-1} and 301 km s^{-1} tangentially with respect to the MW: a net velocity of 302 km s^{-1} (Nichols et al. 2011). The LMC is ~50 kpc from the MW and travelling away at ~89 km s^{-1} radially and 367 km s^{-1} tangentially with respect to the MW: a net velocity of 378 km s^{-1} (Nichols et al. 2011). To conservatively recover all systems where the galaxies are in such spatial-velocity proximity, we create a catalogue of pairs for this work where the projected

[1] http://www.sdss.org/dr6/algorithms/sdssUBVRITransform.html

separation is $r_{\rm sep-proj} < 70$ kpc and the radially velocity separation is $v_{\rm sep-rad} < 400\,{\rm km\,s^{-1}}$. It should be stressed that whilst varying the precise definitions of 'close' and 'similar' does impact the total number of systems recovered and the fractions, it has minimal impact on the ratios between different population fractions.

A consequence of such a selection, and any similar, is that we do not truly distinguish between systems that have close pairs where all three galaxies show signs of independent three-body interactions (e.g. the M81–M82–NGC 3077 group; Yun, Ho & Lo 1994) and systems like the MW–LMC–SMC that had a binary infall formation history (e.g. Bekki 2008; Nichols et al. 2011). In data of GAMA quality there is too little phase space information (two dimensions of high-accuracy spatial positions and one dimension of low-accuracy velocities) to constrain the likely formation history of any system given the selection criteria stated above. Therefore, any fractions quoted should be considered as upper limits for finding systems that had a similar binary infall history to the MW–LMC–SMC but real limits for finding systems with exceptionally small phase separations regardless of the specific formation mechanism (e.g. both MW–LMC–SMC and M81–M82–NGC 3077).

A second point to consider is how sensitive we are to the instantaneous flux of the SMC and LMC, both of which have had complicated star formation histories (e.g. Harris & Zaritsky 2004). Since the complicated tidal interactions between the MW–LMC–SMC are known to trigger a large amount of the star formation (e.g. Zaritsky & Harris 2004), it seems prudent to use the current luminosities and phase positions of all galaxies concerned in order to find analogues. This simplifies the search compared to looking at larger distances because such systems might have entirely different stellar mass content due to experiencing a more quiescent evolutionary history. In fact, Zaritsky & Harris (2004) suggest that as much as 70 per cent of the stellar content of the SMC may have been formed due to interaction triggered star formation.

We use the $r < 19.4$ GAMA-I survey data. Applying these selection limits to recover all systems that have similar pairwise properties to the MW and the Magellanic Clouds creates a catalogue containing 3731 galaxy–galaxy pairs and 6840 unique galaxies with no redshift limits applied. Obviously some galaxies will have more than one pair (the MW has two – the SMC and LMC). We create complexes that contain all galaxy–galaxy associations and count this as a single 'pair' system, i.e. the MW–LMC–SMC as a single 'pair' system. Throughout we use the beta distribution to put robust estimates on the sampling statistics (Cameron 2011), giving us firm limits on the 68th percentile probability range where relevant.

In the LMC depth sample ($0.01 < z_{\rm pair} < 0.089$ for $r < 19.4$ mag), we find 1642 galaxies that have $\mathcal{M}_{\rm s} = \mathcal{M}_{\rm s-MW}$ within a 0.3 dex range. Of these 286 galaxies are the dominant galaxies in the system (240 pairs, 39 triplets, six quartets and one quintet), where there are 340 minor galaxies and 626 galaxies in total. This suggests that 17.4 per cent of MW mass galaxies have at least one 'close' companion. Of these paired systems 56/286 have late-type dominant pair galaxies (19.6 per cent). Of all the systems that have a late-type brightest pair galaxy (BPG), 34 of the minor pair galaxies are late type. Since complexes can contain more than one pair, this translates as 31/56 late-type BPGs that have *at least* one late-type minor companion (55.4 per cent) and 30/56 that have 100 per cent late-type companions (53.6 per cent).

Of these 30 systems that are 100 per cent late-type, all have some observable Hα emission in the larger galaxy (100 per cent) and 32/34 minor companions have some amount of observable Hα emission (94.1 per cent). Comparing to the larger sample of MW mass selected galaxies this means that 30/1642 (1.8 per cent, beta range 1.5–2.2 per cent) of all MW mass galaxies are late-type and in a pair, where all of the minor galaxies are late-type and all galaxies are star-forming. Thus, approximate analogues of the MW system (where we just require all close companions to be Magellanic Cloud like) are rare at the less than 2 per cent level. In this cascade of fractions, the most unusual characteristic is to find a late-type MW mass galaxy in a pair at all, followed by the dominant galaxy being late-type given that it is in a pair. Once these criteria have been met the chance of finding a late-type companion, and star formation in both galaxies, is remarkably high (over 50 per cent). This means that the discussion of the uniqueness of the MW system is largely driven by how rare galaxy pairs are at low redshift.

Three triple systems are present in the final selection. The effective stellar mass limit is less well defined than the r-band limit (which has to assume an approximate k-correction), but based on when the number counts begin to turn over for galaxies with stellar mass less than the SMC the survey is complete out to $z \sim 0.055$. The total observable volume, using the standard cosmology of this paper, is 1.8×10^5 Mpc^3. Two of the three triple systems fall within this redshift range. Since 414 MW stellar mass ± 0.3 dex galaxies are within this redshift limit, full analogues of the MW–LMC–SMC system are rare at the 0.4 per cent level (0.3–1.1 per cent). In terms of space density, we find $1.1 \times 10^{-5}{\rm Mpc}^{-3}$ full analogues in GAMA (in a volume of $1.8 \times 10^5{\rm Mpc}^3$). It is six times more likely that a MW mass galaxy with two SMC mass companions will have early-type morphology. Casting this figure in terms of Gaussian statistics, full analogues of the MW halo are rare at the 2.7σ level when searching around L^* galaxies.

Of the two systems, only one has a minor companion close to the stellar mass of the SMC (the other has two LMC mass companions). This system is the nearest analogue to the MW system found in the GAMA data base, possessing a dominant star-forming spiral galaxy with $\mathcal{M}_{\rm s} = 3.1 \times 10^{10}\,{\rm M_{\odot}}$ ($\mathcal{M}_{\rm s-MW} = 5 \times 10^{10}\,{\rm M_{\odot}}$), a more massive late-type companion with $\mathcal{M}_{\rm s} = 6.1 \times 10^{9}\,{\rm M_{\odot}}$ ($\mathcal{M}_{\rm s-LMC} = 2.3 \times 10^{9}\,{\rm M_{\odot}}$) and a less massive late-type companion with $\mathcal{M}_{\rm s} = 6.1 \times 10^{8}\,{\rm M_{\odot}}$ ($\mathcal{M}_{\rm s-SMC} = 5.3 \times 10^{8}\,{\rm M_{\odot}}$). Both of the companions are more massive than their Magellanic Cloud equivalents, but the smaller one is very close to the mass of the SMC.

While the numbers found in this work suggest that the MW Magellanic Cloud system is cosmologically rare, we at least know that such a combination of galaxy diagnostics is not entirely unique. It is interesting to note that this system does not find the two companions to be in a close binary (as the LMC and SMC appear to be). This is similar to the findings of James & Ivory (2011) who, using an Hα limited imaging survey of 143 spiral galaxies, did not find a single MW Magellanic Cloud analogue that had two companions in a close binary formation. This suggests that the binary nature of the Magellanic clouds might be their defining unique feature.

To compare to the analysis of the Millennium II Simulation by Boylan-Kolchin et al. (2011), we select the 1642 galaxies that are within 0.3 dex of $\mathcal{M}_{\rm s-MW}$ as discussed above. We now apply a mass selection onthe pairs. If we state that any minor pair galaxy must be the mass of the LMC or larger ($\mathcal{M}_{\rm s-LMC} = 2.3 \times 10^{9}\,{\rm M_{\odot}}$), then we find 196 galaxies that have a subhalo occupied by a close companion that is at least that massive. This means that given a halo that is occupied by a MW mass galaxy, there is a 11.9 per cent (11.2–12.8 per cent) chance that a galaxy at least as massive as the LMC occupies a subhalo.

Boylan-Kolchin et al. (2011) find that in haloes that have a MW mass galaxy there will be a subhalo containing a galaxy at least as massive as the LMC 3–8 per cent of the time if the halo is

$\sim 1 \times 10^{12}\,\mathrm{M}_{\odot}$ and 20–27 per cent of the time if the halo is $\sim 2.5 \times 10^{12}\,\mathrm{M}_{\odot}$. The median G^{3}Cv1 halo mass we find for MW mass galaxies is $\sim 2 \times 10^{12}\,\mathrm{M}_{\odot}$ (using the functional A scaling in Robotham et al. 2011). This number is consistent with the halo mass of the MW given by Li & White (2008). Our probability range of LMC or more massive subhaloes (11.2–12.8 per cent) is also between the ranges stated by Boylan-Kolchin et al. (2011), suggesting that it is broadly consistent with their results.

To calculate similar statistics for high-order systems we apply the $0.01 < z < 0.055$ SMC stellar mass depth limit (leaving 414 galaxies), and remove galaxies with stellar mass less than the SMC. We find 14/414 MW mass galaxies that have three or more galaxies in the pair system, i.e. 3.4 per cent (2.7–4.5 per cent) of systems where we expect to be able to observe both the LMC and SMC have at least two galaxies with stellar mass greater than the SMC. The constraint is less tight due to poorer number statistics, a consequence of the smaller parent population within the SMC observable redshift limit. Purely framing the discussion in terms of how likely it is for baryons to occupy subhaloes, these results imply that, assuming that the dominant galaxy in the halo is similar in mass to the MW, it is 3.5 times less likely to have two subhaloes with at least SMC stellar mass compared to one subhalo with at least LMC stellar mass.

4 WHERE DO MAGELLANIC CLOUDS ANALOGUES LIVE?

An actively discussed mechanism for explaining the presence of the Magellanic Clouds in the MW halo is binary infall (see discussion in Bekki 2008; Kallivayalil, Besla & Sanderson 2009; Yang & Hammer 2010; Nichols et al. 2011). This model assumes that the SMC and LMC were a binary pair that entered the MW halo/LG complex simultaneously. Observationally we can determine the viability of such a mechanism by searching first for close binary analogues to the Magellanic Clouds, and then determining the cross-correlation these systems have with various luminosity groups taken from the G^{3}Cv1 (Robotham et al. 2011).

To select close binary Magellanic Cloud analogues (MCAs) we search for all galaxies that have a close companion within a projected separation of 100 kpc and velocity separation of 100 km s^{-1}, where both galaxies are in the range of $-19 < M_r < -17$. This selection conservatively selects all binary pairs with major characteristics in common with the SMC and LMC. 46 such binary MCA systems are found, where 1929 galaxies fall inside the redshift and magnitude selection limits. This implies that 4.8 per cent (4.3–5.3 per cent) of galaxies in the specified magnitude range are in such close binary systems.

Taking the G^{3}Cv1 catalogue we use the cross-correlation approach of Croft, Dalton & Efstathiou (1999) to determine how spatially associated the MCAs are with different luminosity groups (within 0.5 mag of the stated values), where we use the extrapolated r-band flux content given in the G^{3}Cv1 catalogue. Errors are estimated through jackknife resampling (measuring the variance in the cross-correlation signal when binary pairs are excluded) and random volume cones are generated through uniform pointing (within the redshift range explored the sample is complete). The left-hand panel of Fig. 1 shows how closely associated the MCAs are with different types of groups. The medium galaxy flux plotted on the left-hand panel (green line) includes groups with the same flux content as the entire LG. The red line shows more massive systems than the LG, and the blue line includes groups with the same total flux as just the MW halo. It is clear that MCAs are more likely to be found in proximity to LG mass complexes, suggesting that the presence of M31 near to the MW halo has enhanced the probability of observing a binary system like the SMC–LMC. A caveat to this result is the cross-correlations that are affected by the subset comparisons chosen, and given the known interplay between luminosity and interactions the systems detected at large separations are likely to be in a different evolutionary state to those at close separations.

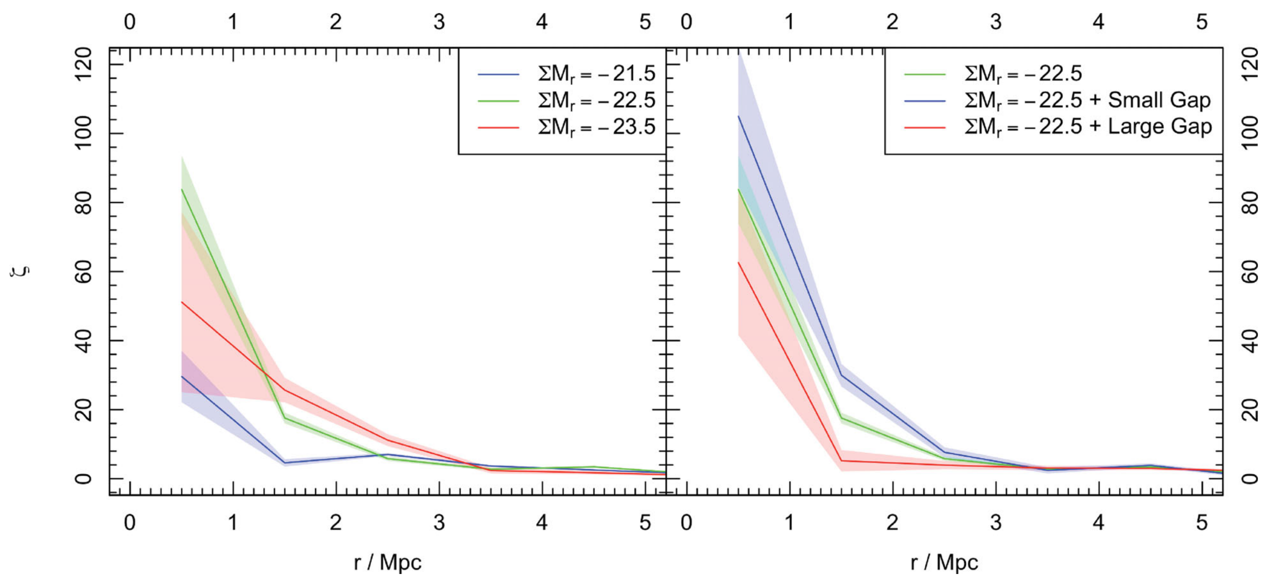

Figure 1. Left-hand panel shows the cross-correlation between close binaries that are analogues to the SMC/LMC pair (Magellanic Cloud analogues: MCAs) and G^{3}Cv1 groups of different extrapolated flux content within 0.5 mag of the value stated in the legend. The total r-band magnitude of the Local Group is $M_{r-\mathrm{LG}} = \sim -22.2$, and the total magnitude of the MW halo is $M_{r-\mathrm{MW}} = \sim -21.3$. The right-hand panel splits the most highly clustered MCA-group subset ($\Sigma M_r = -22.5$) into two further subsets: one with $M_{r-2^{\mathrm{nd}}} - M_{r-1^{\mathrm{st}}}$ less than the median magnitude gap value of 0.7 for the groups selects and another with $M_{r-2^{\mathrm{nd}}} - M_{r-1^{\mathrm{st}}}$ larger than the median. In both plots the y-axis is the standard cross-correlation excess, and is the relative excess compared to the random volume.

To further investigate the effect seen for $\Sigma M_r = -22.5$ groups, this cross-correlation was subdivided into two subsets: one where the magnitude gap of the brightest two galaxies ($M_{r-2^{\rm nd}} - M_{r-1^{\rm st}}$) is larger than the median value of 0.7 (so the central galaxy dominates) and another where the magnitude gap is smaller than the median (so the central galaxy does not dominate). The right-hand panel of Fig. 1 shows the cross-correlations for these two subdivisions, with the original full sample plotted also. There is a marginally significant preference for MCAs to be more spatially associated with groups with small magnitude gaps. These systems should be dynamically less evolved since the central galaxy is not as dominant within the group, and in fact is one of the major characteristics of the LG: the MW and M31 are similarly massive galaxies that would be found in the 'small gap' sample. These data lend evidence that the MW halo should not be considered in isolation when determining the occupation probability of the Magellanic Clouds. The potential role of M31 on the presence of the LMC and SMC near the MW has been considered in recent simulation work (e.g. Kallivayalil et al. 2009; Yang & Hammer 2010), suggesting that its presence might be significant rather than coincidental.

To quantify this effect differently we move from considering the cross-correlation of MCAs with groups, to directly searching for L^* pairs in close proximity. We create the L^* pair sample by searching for all galaxies in the range of $-21.9 < M_r < -20.9$ (the MW and M31 fall well inside this selection), within $r_{\rm proj} < 1000$ kpc and $v_{\rm sep} < 500\,{\rm km\,s^{-1}}$. Of the 302 galaxies that fall within the magnitude selection 96 (32 per cent) have a close L^* companion (i.e. there are 48 pair systems). For each pair system we calculate the effective r-band centre of light in RA, Dec. and redshift, and define this as the centre of the pair system. We now search for all MCAs that are within a $r_{\rm proj} < 1000$ kpc and $v_{\rm sep} < 500\,{\rm km\,s^{-1}}$ separation to L^* pair systems. 11/47 MCAs are found in close proximity to L^* pair systems, while 27/47 MCAs are found within the same spatial separation of *any* L^* galaxy. At a maximum the effective comoving volume searched over for all L^* systems is $1.3 \times 10^4\,{\rm Mpc^3}$, which is ~7 per cent of the available GAMA volume within these redshift limits. For the L^* pairs the maximum volume searched is $2.1 \times 10^3\,{\rm Mpc^3}$, which is ~1 per cent of the available GAMA volume. Consequently, we find that 57 per cent of MCAs are found within 7 per cent of the volume when searching around L^* systems, and 23 per cent of MCAs are found within 1 per cent of the volume when searching around the centres of L^* pairs. There is a clear tendency for MCAs to be associated with L^* systems in general (rather than just random distributed throughout the Universe), and an even stronger association is seen between MCAs and binary pairs of L^* galaxies, such as the MW and M31.

The best MMA (constituting a spiral brightest galaxy and star-forming companions, known as GAMA-MMA1) also has a nearby companion spiral galaxy. A multicolour image based on Sloan Digital Sky Survey (SDSS) photometric data is shown in Fig. 2. Table 2 contains key information on the system. The companion spiral is 190 kpc away in projection (MW and M31 are separated by 800 kpc in real space) and $-400\,{\rm km\,s^{-1}}$ separated in velocity (M31 is moving at $-122\,{\rm km\,s^{-1}}$ radially and ~$100\,{\rm km\,s^{-1}}$ tangentially with respect to the MW). These two spirals have $M_r = -21.43/-21.31$, which is very similar to MW/M31 ($M_r = -21.47/-21.17$). Integral Field Unit (IFU) and Parkes data have recently been obtained for this newly identified analogue to the LG system, and we are actively seeking follow-up on a sample of the MMAs discussed in this work in order to better quantify the occupation statistics in haloes similar to our own.

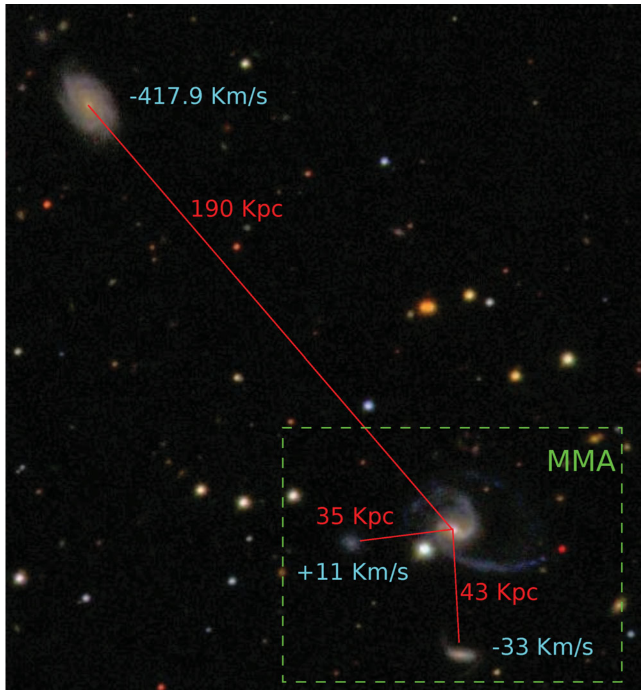

Figure 2. SDSS image of the best LG analogue found in GAMA. The spiral galaxy in the bottom right with the two indicated brighter companions is the MMA (GAMA-MMA1), where all three galaxies are late-type and star-forming, making this system similar to the MW Magellanic Cloud system in the most fundamental ways. An associated nearby spiral galaxy is also shown.

Table 2. Basic information for a particularly striking example of a Milky Way Magellanic Cloud Analogue (GAMA-MMA1) with a nearby bright spiral companion. This mimics a lot of the most recognizable characteristics of the MW–SMC–LMC and M31 complex.

GAMA ID	RA (J2000)	Dec. (J2000)	Redshift	m_r
MMA				
202627	08:42:28.28	−00:16:17.8	0.05130	15.25
202636	08:42:28.13	−00:17:00.7	0.05134	17.25
202691	08:42:30.64	−00:16:22.3	0.05119	18.47
Close spiral				
202673	08:42:36.66	−00:13:51.5	0.04991	15.31

5 CONCLUSIONS

The major findings of this work are summarized below.

(i) Analysing all galaxies within 0.3 dex of the stellar mass of the MW, there is a 11.9 per cent (11.2–12.8 per cent) chance that it will have a close companion (within a projected separation of 70 kpc and radial separation of $400\,{\rm km\,s^{-1}}$) that is at least as massive as the LMC. This is consistent with analyses by Boylan-Kolchin et al. (2011) of the Millennium II Simulation and by James & Ivory (2011) of Hα imaging around luminous spiral galaxies.

(ii) Limiting the sample to those galaxies where the SMC would be observable we find that 3.4 per cent (2.7–4.5 per cent) of galaxies have two companions at least as massive as the SMC.

(iii) Only two full analogues to the MW–LMC–SMC system were found in GAMA, suggesting that such a combination of late-type, close star-forming galaxies is quite rare: in GAMA only

0.4 per cent (0.3–1.1 per cent) of MW mass galaxies have such a system (a 2.7σ event). In terms of space density, we find 1.1×10^{-5} Mpc^{-3} full analogues in GAMA (in a volume of 1.8×10^{5} Mpc^{3}). The best example found shares many qualitative characteristics with the MW system. The BPG has spiral features, as does the bigger minor companion. The minor companions are $\sim$40 kpc in projected separation, so not in a close binary formation such as the SMC and LMC.

(iv) Selecting systems that are close binaries like the SMC–LMC pair (MCAs), we find that they are preferentially located in close proximity (or within) systems that have a similar total flux to the LG ($\Sigma M_r = -22.5 \pm 0.5$ mag).

(v) Subdividing the preferential group type into those with large and small magnitude gaps, we find that MCAs are more spatially associated with groups that have a small magnitude gap. This suggests that a quiet recent merger history improves the likelihood of the Magellanic Clouds being visible in the LG. The best MMA analogue found in GAMA also has a close L^* spiral companion galaxy.

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